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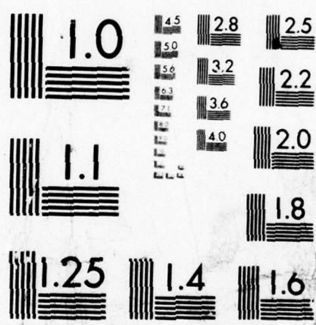

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STRONG FAR-AWAY EFFECTS OF LOCAL CLOUD SEEDING

PROGRESS IN TECHNOLOGY DEPENDS ON INTENSE STUDIES OF THESE PHENOMENA

JERZY NEYMAN

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13. ABSTRACT

The Public Law 94-490 of 1974 directs the Secretary of Commerce to formulate an appropriate national policy on weather modification. This event stimulated publication of "A statistician's view of weather modification technology," (Proc. Natl. Acad. Sci., Vol. 74, 1977). The present Technical Report is similarly motivated. It assembles evidence of an unexpected phenomenon: the seeding of clouds intended to affect the precipitation in a conventional target, perhaps some 50 km across, appears to have strong effects on rain at distances of 140-280 km, "the far-away effects." The hypothetical atmospheric physics mechanism described in the Report explains some of the empirical findings, but not all. The particularly interesting unexpected finding refers to the seven year long Arizona experiment: an apparent 74% increase in rain ($P=0.047$) in far-away localities on the right of the day's wind direction. The statistical methodology used is a combination of "moving grids" and of optimal $C(\alpha)$ tests.

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Public Law 94-490, enacted in October, 1976, directs the U.S. Secretary of Commerce to formulate an appropriate national policy on weather modification. While the whole domain is vast, the thinking of the general public and of many scholars focuses on the so-called cloud seeding as a means to enhance precipitation, rain or snow.

In a recent article (1) I showed that, because of lack of randomization or because of defects in its implementation, the claims of success on the part of cloud seeding industry are not trustworthy. Also, the same article documents that the many reports from apparently authoritative sources are slanted and unreliable. On the positive side, the same article noted the phenomenon of unexpectedly large apparent effects of local cloud seeding observed at unexpectedly distant areas. This phenomenon, observed in two seven-year long experiments conducted with marked effort at strict randomization, appears as a most promising object of future studies.

The above general picture of precipitation augmentation technology is confirmed by the recently published document (2) dated June 30, 1978. This document, The Management of Weather Resources, addressed to the Secretary of Commerce, has been formulated by the Weather Modification Advisory Board chaired by Harlan Cleveland. Interestingly, the Board recognized the necessity to create a Statistical Task Force and there appeared a lack of unanimity. This is reflected in the contents of the two-volume Report published by the Board. Volume II represents the Report of the Statistical Task Force to the Board as a whole. According to Harlan Cleveland (Vol. II, p. ii), "The Board's own judgements do not always follow the statistical findings to their ultimate inconclusiveness." The attitude of the Statistical Task Force is illustrated by the following three quotations: (i) "randomization has come to be recognized as an essential part of gathering trustworthy data about weather modification." (ii) "randomization...needed if we are to be able to use the results as solid evidence." (iii) "The details--and not just summaries--need to be available...". While I am in full agreement with all the three items quoted, I am especially appreciative of item (iii) being published in the Report of the Advisory Board.

The Statistical Task Force was composed of three persons: David R. Brillinger, Lyle V. Jones and John W. Tukey, Chairman. The studies of this Task Force seem to have been limited to a few latest substantial experiments. The "strong far-away effects of local cloud seeding" were noticed in experiments performed earlier. The data of these experiments indicate that "local" seeding of summertime clouds may have far-away effects that are stronger than those at the site of seeding. In some cases, the seeding of clouds in a "target" A appears to double the rainfall in a far-away locality B. But in some other cases, the seeding at A appears to reduce the rain in B to one-half or even to one-third of what would have fallen without seeding. If these indications reflect real phenomena, then the understanding of the underlying atmospheric mechanism would constitute a very important contribution to the weather modification technology.

The purpose of the present paper is to assemble the evidence relating to the far-away effects of local seeding of summer cumulus clouds and to indicate a hypothetical mechanism thereof. This mechanism explains some of the empirical findings, but not all. In particular, the large far-away increases in rainfall apparently due to seeding that occurred in certain circumstances are not explained. Here, then, an appeal for cooperation of interested atmospheric physicists is in order.

The plan of this paper is as follows. First, the meaning of the somewhat vague terms "far-away effects of local seeding" is clarified. Next, evidence of far-away effects of local seeding is presented, stemming from two experiments, one in Switzerland and the other in Arizona. This is followed by the description of the hypothetical mechanism that explains a substantial part of empirical findings. Finally, certain findings of in-depth studies are pointed out that the proposed mechanism fails to explain.

Figures 1 and 2 are intended to illustrate the meaning of the terms "local cloud seeding" and "far-away effects" thereof. Fig. 1 gives a schematic map of a region that includes substantial parts of Switzerland and of Italy. The word Ticino marks the approximate location of the Swiss canton bearing this name. During the summers of seven years, 1957-1963, the Canton Ticino was the "target" of a randomized cloud seeding experiment (3) Grossversuch III. The purpose of the experiment was to verify the hypothesis that the seeding of clouds with silver iodide (AgI) smoke will suppress hail. However, rainfall was also a subject of study. In the present paper the discussion of Grossversuch III is limited to rainfall. The AgI smoke was dispersed from a number of generators mounted on tops of hills surrounding the intended target.

The seeding in Ticino exemplifies the meaning of the term "local cloud seeding." In order to illustrate the term "far-away effects," Fig. 1 exhibits seven shaded areas located around Ticino. Two of these areas, marked Zürich and Neuchâtel, are in Switzerland. I am indebted to Dr. Max Schüepp of the Swiss Central Meteorological Office for providing rain data from 20 raingages in each of these two areas. The remaining 5 shaded areas in Fig. 1 are in northern Italy. Here, the number of gages per area varied from 7 to 15.

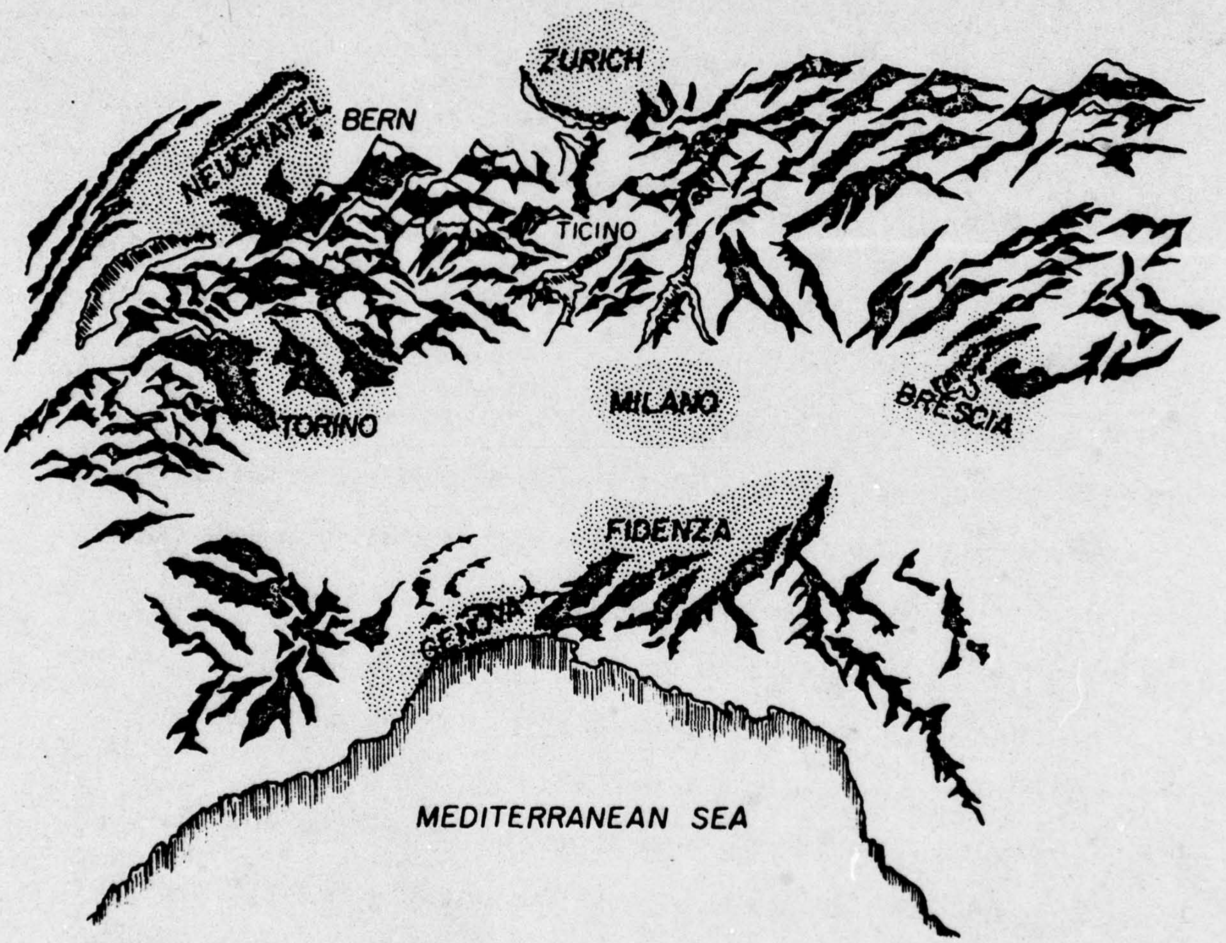


Fig. 1. Area of Grossversuch III.

The "as the crow flies" distances of the seven shaded areas in Fig. 1 from the Canton Ticino are large. For example, the distance of the Zürich area is of the order of 120 km. and that of the Neuchâtel area of the order of 180 km. Both these areas are separated from Ticino by the impressive bodies of the Alps. In the *a priori* unlikely event that the seeding of clouds over Ticino affected the rainfall in any of the shaded areas in Fig. 1, such effects would be termed "far-away effects of local cloud seeding".

As will be described below, very large apparent "far-away effects" of local cloud seeding over Ticino did actually occur. Depending upon atmospheric conditions, such as inversions and winds aloft, they were "positive" or "negative". However, this happened in very special climatic and topographic conditions: in the vicinity of the Mediterranean and near the impressive Alps. The important question is whether any similar phenomenon is noticeable elsewhere. Here, Fig. 2 is relevant.

Figure 2 gives a schematic map of an area in Arizona. Here, over the summer months of seven years, a randomized cloud seeding experiment was performed (4) by Louis J. Battan, Professor at the University of Arizona, Tucson. The experiment was composed of two parts labeled "Programs". Program 1 extended over four years, 1957-1960, and Program 2 over three years, 1961, 1962 and 1964. The intention of the experiment was to verify the hypothesis that cloud seeding over the Santa Catalina Mountains could increase the rainfall. The second program differed from the first principally in the following respects: (i) the target area in the Santa Catalinas was somewhat smaller, (ii) the number of gages (all recording gages) was increased, (iii) the definition of a "suitable" day was somewhat more stringent, and (iv) the level above the ground at which the AgI smoke

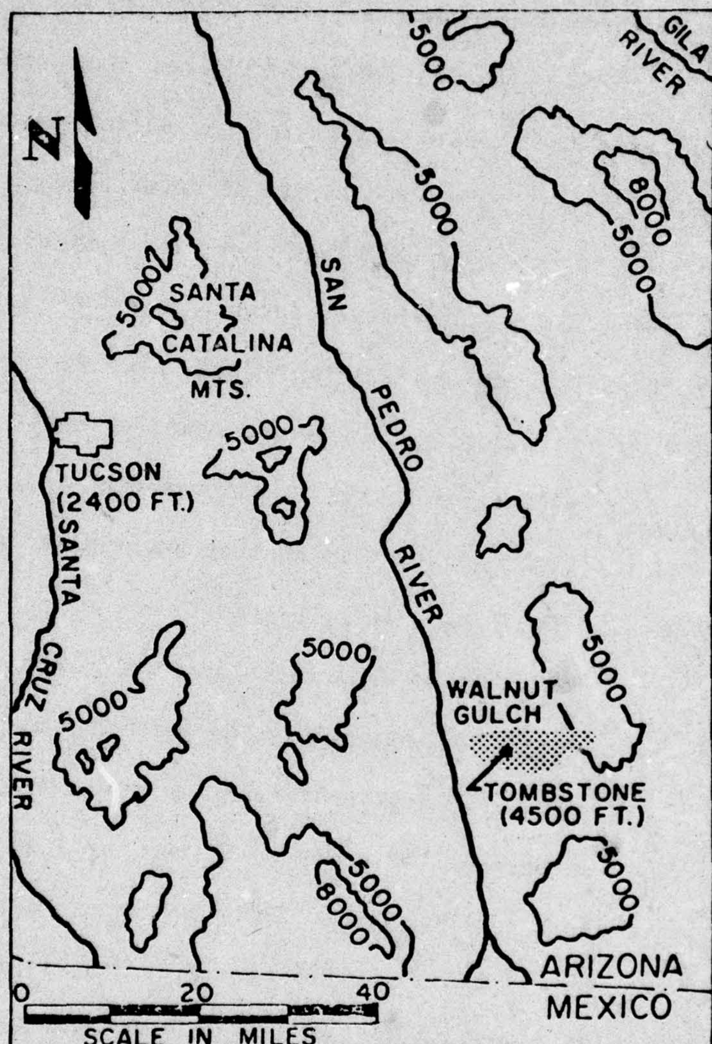


Fig. 2. Area of the Arizona experiment.

was dispersed by a seeder airplane was altered. Basically, Battan's evaluation of the experiment contains two parts, one each for the two Programs. However, some questions were studied using all the available data combined. Here, then, the seeding over the target in the Santa Catalinas (some 32 km. across) represents "local cloud seeding".

In addition to this target, Fig. 2 exhibits a small shaded area, some 100 km. to the SSE from the Santa Catalinas. This shaded area marks Walnut Gulch, where the U.S. Department of Agriculture maintains a very dense network of recording raingages, intended for the investigation of a variety of phenomena such as soil erosion, etc. The person in charge of the Walnut Gulch network is Dr. Herbert B. Osborn. A cooperative study with Osborn (5) indicated that, on days when Walnut Gulch was approximately "downwind", the "local cloud seeding" over the Santa Catalinas was marked by very large seed-no seed difference in rain in Walnut Gulch. If "real", that is, if not caused by vagaries of randomization, then the term "far-away effect of local cloud seeding" would apply to this phenomenon.

Our studies of far-away effects of local seeding were motivated by the question about the validity of the cross-over experimental design. As described by E.J. Smith (6), the cross-over design originated in Australia. In this design there are two "targets," say T_1 and T_2, not very distant, so that the time periods (perhaps days) that are judged "suitable" for cloud seeding in one of them are also suitable for seeding in the other. Then, experimental cloud seeding is performed on all days that are judged suitable in the general locality containing T_1 and T_2. When such a day arrives, a randomized decision is made as to whether to seed in T_1 or T_2. This procedure doubles the number of observations possible during a given experimental season, which is a considerable gain. In addition, the theory developed by P.A.P. Moran (6) indicates a very advantageous possibility of using the non-seeded target as a control area for the other target.

Obviously, if no far-away effects of local seeding exist, then the cross-over design is very attractive, which explains its frequent use. But what if seeding over T_1 produces a substantial effect on precipitation in T_2, and vice versa?

Prior to describing our efforts to study the far-away effects of seeding at Grossversuch III, it is necessary to mention briefly an earlier finding. This is that the effects of seeding on rain in Ticino itself depended on the presence or absence of stability layers (inversions or thick isothermals) as revealed by the noon radiosonde at Milan (7). It appeared that, in the presence of stability layers the apparent effect of seeding on rainfall in Ticino itself was a large and significant increase in rain. On the other hand, on days with uninhibited updrafts, the apparent effect of seeding was also large, but negative and not quite significant by customary standards. Because the effectiveness of silver iodide as a nucleating agent of ice crystals is limited to supercooled clouds, with temperatures below $-5^{\circ}C$, both findings appeared unexpected. However, independent studies of Neiburger and Chin at U.C.L.A. (7) and of M. Schüepp and J.C. Thams of Zürich (unpublished) provided a convincing explanation of the enhancement of rain by seeding under stability layers. On the other hand, the absence of large increases in rain on days with uninhibited updrafts appeared mysterious. As a consequence of these findings, the later effort to see whether the local seeding in Ticino was accompanied by the far-away effects in the shaded areas of Fig. 1, was conducted with a stratification: separately for days with uninhibited updrafts and separately for days with stability layers.

Evidence of Far-Away Effects of Seeding in Grossversuch III

The results of our first effort to study the possibility of far-away effects of seeding over Ticino are exhibited in Table 1 reproduced from (8).

It is seen that, in the presence of stability layers, the local seeding in Ticino was accompanied by excesses of rain in all the 8 localities studied, that in 6 of these localities the apparent increases in rain were greater than 40% and that in 3 of them they were significant (two-tail P) at better than 5%. On the other hand, on days with uninhibited updrafts the apparent effects in 6 areas were negative, but none of them significant by customary standards.

Confronted by the results for days with stability layers, particularly with significant apparent gains of more than 50% in rain near Zürich and Neuchâtel, Dr. Schüepp was incredulous and made two suggestions. According to Schüepp, the principal source of moisture in the atmosphere over Switzerland is the Mediterranean, in the south. Thus, if one stratifies the Grossversuch III experimental days according to wind directions with velocity components from the south vs. those from the north, the study of rainfall data in the eight areas might contribute to the hypothesis of causality with seeding in Ticino. Schüepp's other suggestion was to investigate the timing of the apparent effects of seeding in the various areas.

Table 1

Effects of Grossversuch III seeding in Ticino on rainfall in millimeters, fallen in 8 areas, averaged per experimental day.
S = mean precipitation on seeded days, NS on not seeded
P = significance probability

	Days with uninhibited updrafts 47 seeded, 50 not seeded				Days with stability layers 96 seeded, 94 not seeded			
Area	S	NS	% change	P	S	NS	% change	P
Zürich	4.54	7.04	-35	0.11	6.98	4.19	+67	0.012
Neuchâtel	4.43	5.86	-24	0.32	6.84	4.36	+57	0.037
Ticino	7.98	12.45	-36	0.15	14.47	8.82	+64	0.031
Brescia	4.18	6.65	-37	0.079	6.09	4.17	+46	0.066
Turin	4.24	4.07	+ 4	0.90	5.61	5.41	+ 4	0.89
Milan	2.93	3.78	-22	0.43	5.68	3.90	+45	0.13
Fidenza	3.76	3.94	- 5	0.87	5.26	3.68	+43	0.15
Genova	3.73	3.20	+16	0.65	4.24	3.65	+16	0.60

Table 2 reproduced from (8) and Fig. 3 give the results of these studies.

The wind directions used to produce the results in Table 2 are those published in the annual reports on Grossversuch III. They are based on the noon radiosonde at Milan at the altitude of 1,500 meters above sea level. In interpreting Table 2 one must bear in mind two circumstances. One is that the terms "southerly" and "northerly" winds are subject to interpretation. A particular day in the "southerly" category could have a wind with a strong easterly velocity component and only a very weak component from the south, etc. Another important circumstance is that many of the raingages used were located in deep canyons with varying directions. The combination of these two factors must have contributed to the many irregularities in the general pattern of Table 2.

However, the stability layers part of Table 2 does reveal a contrast between the apparent seeding effects on southerly and northerly wind days. In particular, the apparent increases in rain in Ticino and near Zürich with southerly winds exceeded 100% and their significance probabilities became impressive. This is in contrast with the part of Table 2 for days with stability layers and northerly winds. The general impression favoring causality between seeding and the indicated pattern of rain in far-away localities is increased by Fig. 3.

Fig. 3 refers to days with stability layers. It is based on hourly precipitation data kindly provided by Dr. Schuepp. Fig. 3 has two panels, one for southerly and the other for northerly winds, and each panel exhibits two curves, one for days seeded in Ticino and the other for controls. The vertical lines mark the scheduled period of seeding in Ticino, 14 hours beginning at 7:30 a.m.

Table 2

Effects of seeding in Ticino on the rainfall in 8 areas on days with and without stability layers, with low southerly and northerly winds.

S = mean precipitation on seeded days, NS on not seeded

P = significance probability

Area	S	NS	% effect	P	S	NS	% effect	P
	Days with uninhibited updrafts				Days with stability layers			
	Days with low southerly winds							
	25 seeded, 22 not seeded				48 seeded, 46 not seeded			
Zürich	5.22	7.20	-27	0.39	8.81	4.07	+116	0.004
Neuchâtel	5.51	7.22	-24	0.46	8.48	5.16	+ 64	0.060
Ticino	12.40	19.21	-35	0.23	17.78	8.61	+106	0.018
Brescia	5.38	9.85	-45	0.11	6.30	4.75	+ 33	0.33
Turin	5.65	4.87	+16	0.73	6.29	3.27	+ 93	0.063
Milan	3.96	5.60	-29	0.44	4.67	3.46	+ 35	0.42
Fidenza	3.43	6.01	-43	0.23	3.44	3.15	+ 9	0.81
Genova	3.96	3.91	+ 1	0.98	2.76	3.00	- 8	0.84
	Days with low northerly winds							
	19 seeded, 25 not seeded				42 seeded, 37 not seeded			
Zürich	4.32	6.90	-37	0.29	5.38	4.05	+ 33	0.41
Neuchâtel	3.55	4.19	-15	0.71	5.48	3.54	+ 55	0.27
Ticino	3.28	4.80	-32	0.42	11.03	8.76	+ 26	0.56
Brescia	3.14	3.71	-15	0.62	6.22	3.72	+ 67	0.11
Turin	2.98	3.27	- 9	0.86	5.02	9.18	- 45	0.15
Milan	1.95	2.46	-21	0.60	7.26	5.07	+ 43	0.31
Fidenza	4.43	2.47	+79	0.11	7.92	5.11	+ 55	0.23
Genova	3.80	2.80	+36	0.51	6.31	5.28	+ 19	0.66

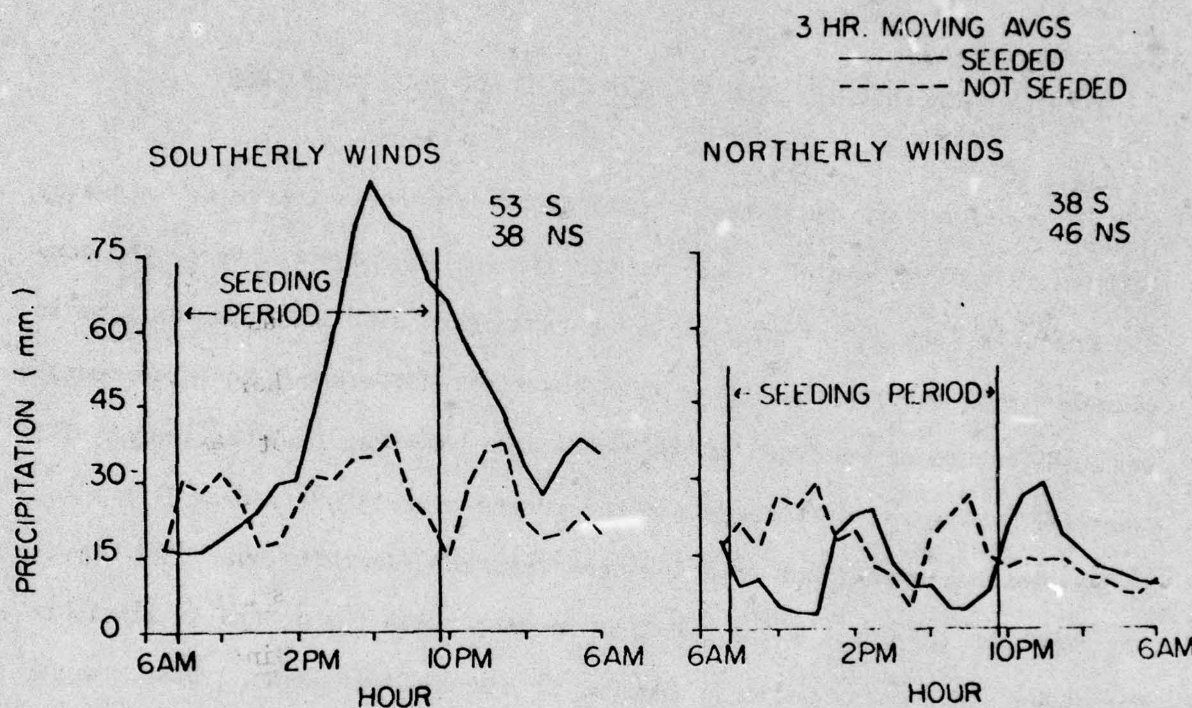


Fig. 3. Diurnal variation in hourly rainfall in Zurich when it was approximately downwind and when it was approximately upwind from Ticino.

It is seen that the average hourly rainfall in Zürich on seeded days with southerly winds began to markedly exceed that on days without seeding some time in the afternoon, 5 to 7 hours after the scheduled commencement of seeding. This difference continued for quite a few hours. No such striking effect appears noticeable on days with northerly winds.

Evidence of Far-Away Effects of Seeding in Arizona

As mentioned at the outset, the second source of evidence of far-away effects of seeding summer clouds is the Arizona experiment. Here, the conditions were very different from those in Grossversuch III. In addition to climate and topography, there were important differences in experimental design: method of seeding and randomization. Whereas in Grossversuch III the AgI smoke was dispersed from the ground over 14 hrs., from 7:30 a.m., in the Arizona experiment this was done from an aircraft over 2-4 hrs., beginning at 12:30 p.m. The level of seeding above the ground is likely to have been above warm stability layers, if any were present. Also, while the Grossversuch practice approximated a 50:50 unrestricted randomization, the design in Arizona was in not completely randomized pairs of "suitable" days, subject to the restriction that the two days of a pair be separated by not more than one day diagnosed as "not suitable". For the first day of each pair, the decision whether to seed or not was purely random. Whatever this decision was, it required a contrary decision for the second day. If the first day of a prospective pair was followed by two non-suitable days, then this first day of the incipient pair was discarded and the continuation of the experiment awaited the arrival of another day diagnosed "suitable," that could become the first day of an incipient pair, etc. In consequence, the second days of all the experimental pairs, 106 of them, are marked by the fact that their suitability was diagnosed with full knowledge whether they would be seeded or not. This circumstance requires that evaluations, whether of the entire experiment or of a stratum, be in a sense "triple": (i) all days, (ii) first days of pairs and (iii) second days.

Table 3, part of the table published in (9), gives the apparent effects of Santa Catalina Mountains seeding on the noon to noon 24 hrs. rainfall in Walnut Gulch, averaged for experimental day, whether wet or dry. These results for Walnut Gulch are compared with similar data for the 24 hrs. precipitation in the Santa Catalina target itself. Symbol P denotes the two-tail significance probability.

Symbol NW marks days with northwesterly winds on which Walnut Gulch was approximately downwind from the site of seeding. Symbol SE stands for days with southeasterly winds, that is, all experimental days other than those marked NW. The directions of winds are those of the level of seeding as recorded by the 5 p.m. radiosonde at Tucson.

It is seen that, while all the apparent effects in Table 3 are negative, the two stratifications of days, namely NW (when Walnut Gulch was approximately downwind) vs. SE days and the stratification of 1st days vs. 2nd days, exhibit interesting contrasts. On NW days, the apparent loss of rain in the Santa Catalinas is negligible, but at Walnut Gulch it is very large and highly significant. This is contrasted on SE days: a significant 40% loss of rain in the Santa Catalinas vs. a moderate and a non-significant loss in Walnut Gulch. The contrast for the second stratification is less striking but it is in the same general direction: the stratum which is less favorable in one of the two localities is more favorable in

Table 3

Apparent effects of cloud seeding over Santa Catalina Mountains on 24-hour precipitation in target and in Walnut Gulch, Arizona. (Both Programs are included.)

	Rainfall over Santa Catalina			Rainfall over Walnut Gulch		
Category	Inches	%E	P	Inches	%E	P
All days						
S	0.125	-30	0.06	0.093	-40	0.02
NS	0.179			0.155		
NW wind						
S	0.120	- 9	0.78	0.039	-73	0.01
NS	0.133			0.142		
SE wind						
S	0.127	-40	0.03	0.115	-31	0.17
NS	0.211			0.166		
1st days						
S	0.126	-34	0.13	0.115	-14	0.63
NS	0.189			0.134		
2nd days						
S	0.125	-35	0.31	0.075	-58	0.01
NS	0.166			0.181		

the other.

The results for all experimental days of the Arizona experiment indicate a 30% apparent loss of rain in the target, significant at 6% and a 40% apparent far-away loss, significant at 2%.

Figure 4, reproduced from (1), indicates that the striking seed day rain deficiencies when Walnut Gulch was approximately downwind from the seeding site began to be impressive at about 5 or 6 p.m. and lasted past midnight.

Hypothetical Mechanism of Far-Away Effects of Local Seeding of Summer Clouds

The above results, suggestive of the far-away effects as they are, have been obtained by a somewhat crude method. In order to study the downwind effects, the experimental days with radiosonde data, 287 of them in Grossversuch III and 210 in Arizona, had to be split into two parts, one with the areas of interest being approximately downwind and the other with these areas being upwind. Any further stratifications required the analysis to be made on a relatively small number of observations, with the consequent decrease in precision. A somewhat more in-depth methodology, provides the possibility of studying the wind direction influences using all the available experimental data simultaneously. This methodology, labeled "moving grid" or "mogrid" methodology, was developed (10) using the idea of R.R. Braham who developed it for radar data.

The study of the Arizona experiment using the mogrids (11) ends with the following sketch of a hypothetical mechanism (HM, for short) of the far-away

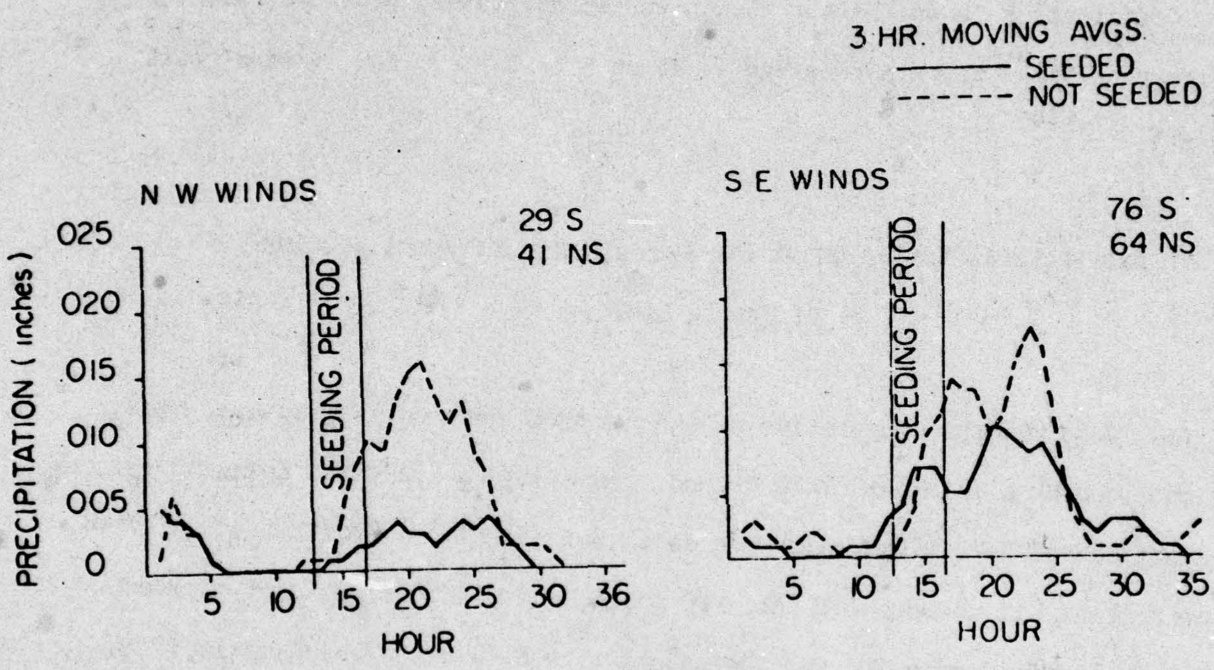


Fig. 4. Diurnal variation in hourly rainfall in Walnut Gulch when it was approximately downwind and when it was approximately upwind from Santa Catalina Mountains.

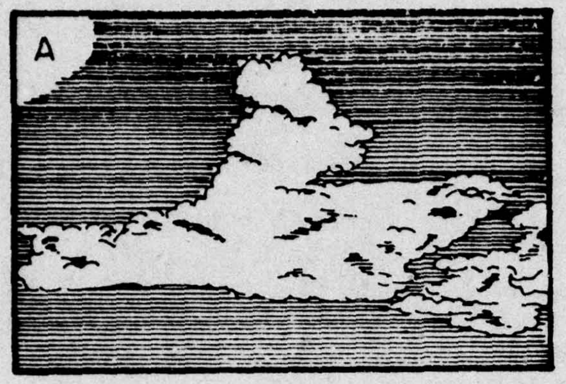
losses of rain:

"The seeding may have initiated rain high above the ground; when falling through dry air, this rain evaporated and decreased the temperature; while carried downwind, the parcel of cool air eventually reached the ground and inhibited convection."

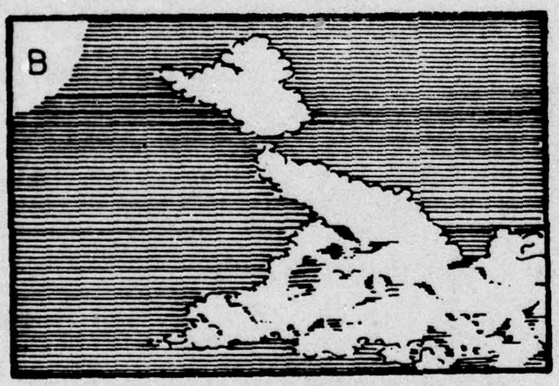
The relevance of the evaporation of rain before it reaches the ground seems to have been first noticed in 1962 by E.J. Workman. I regret that I overlooked his publication for a long time. Subsequent studies are due to Schüepp, J. Joss and H.P. Roesli (12).

We now proceed to assemble empirical evidence favoring the above hypothetical mechanism. Indications are that this mechanism operated not only during the Arizona experiment, but also on the uninhibited updraft days of Grossversuch III. However, some of the evidence indicates a phenomenon not implied by the HM: large increases in rainfall occurring in certain conditions. The atmospheric-physical aspect of these conditions appears as a very important problem.

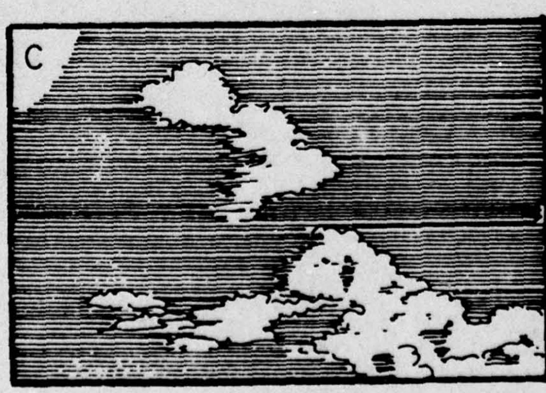
Figure 5, redrawn from a figure published by J. Simpson and A.S. Dennis (13), illustrates the happenings to a summer cumulus cloud subjected to seeding. The legend states that the figure represents photographs illustrating the "cut-off tower regime which often follows dynamic seeding of a single cumulus." With reference to HM, Fig. 5 illustrates the fact that the rain initiated by seeding can establish a "cut-off tower regime," presumably by cooling the lower part of the cloud. The term used by the two authors is "precipitation break." This, however, does not document anything about the Arizona experiment. Certain happenings at the Arizona experiment are illustrated by Fig. 6. This figure illustrates the patterns of winds aloft recorded by the 5 p.m. radiosonde at Tucson. These observations exist for



PANEL A: Cumulus at time of seeding.



PANEL B: Same cumulus 10 minutes after seeding.



PANEL C: Same cloud, split into two parts,
18 minutes later.

Fig. 5. "Cut-off tower regime which often follows dynamic seeding of a single cumulus."

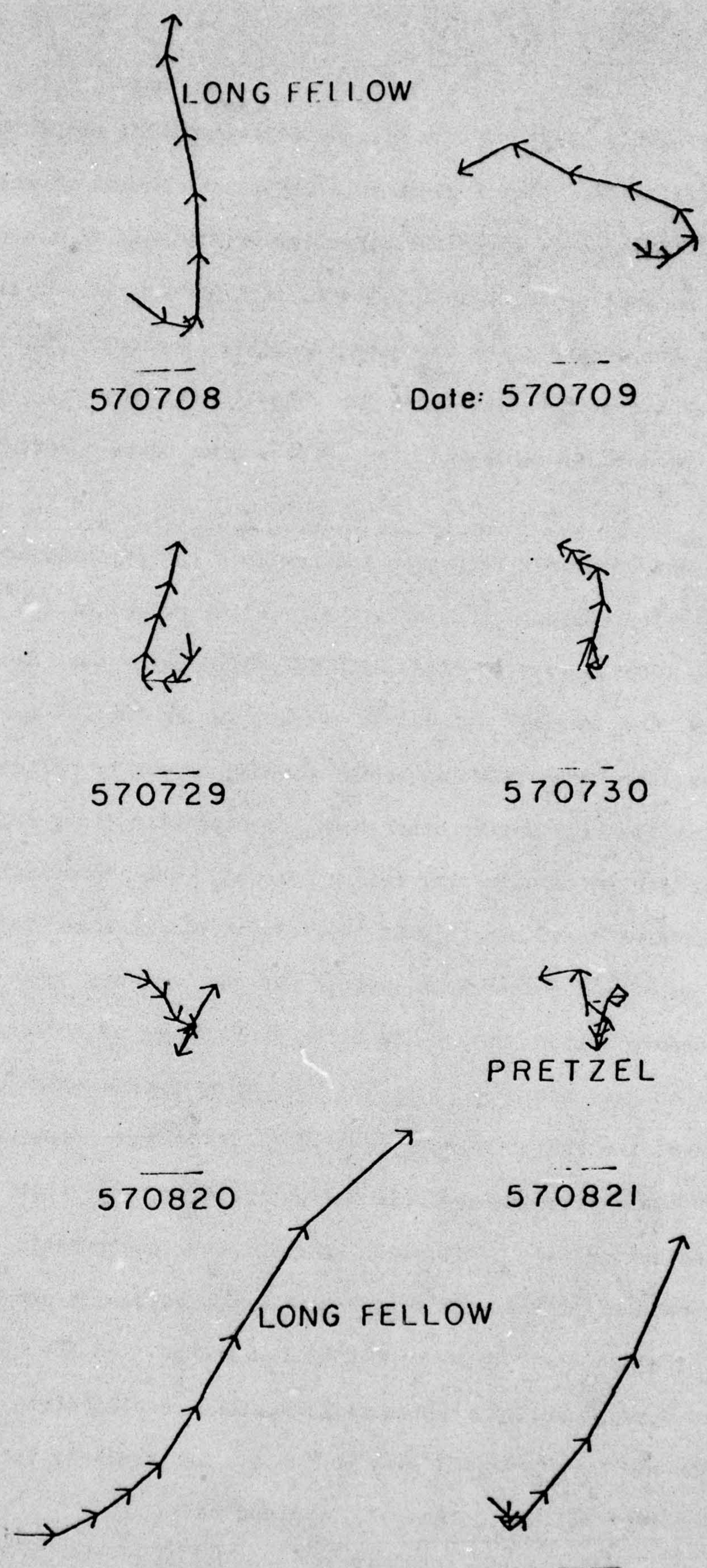


Fig. 6. A sample of wind patterns aloft at 5 p.m. of experimental days during the Arizona Trial.

210 experimental days of the Arizona experiment for which the radiosonde data are available. Fig. 6 gives an illustrative sample of the data. Each vector of a sequence gives the direction of the wind at a specified level above the ground, measured in millibars, from 900 mb. to 200 mb. Also the length of the vector gives the wind velocity. A closer inspection of Fig. 6 indicates two contrasting types for which the workers at Berkeley Statistical Laboratory invented the descriptive terms "pretzels" and "long fellows."

The term "pretzel" refers to the regime of practically no winds aloft that prevailed during the relatively brief period of the ascent of the radiosonde. Obviously, on days with seeding over the Santa Catalinas marked by the pretzel winds occurring during the 2-4 hours of seeding operations, the "precipitation break" phenomenon can be reflected only in the target itself. On the other hand, on days with "long fellow" winds at an appropriate level occurring during seeding, the "precipitation break" must be carried away, possibly to manifest itself in some other locality.

The important question is whether any such effects are reflected in actual precipitation data. The relevant findings of Professor Battan are published in two papers (4). In his 1967 paper Battan shows that on days with seeding over the Santa Catalina Mountains, there were relatively more radar echoes in the clouds than on days without seeding, and that this difference, indicating the initiation of rain, was concentrated on clouds with top temperatures between -24°C and -30°C, very cold. It seems likely that these clouds had their bases high over the ground. In the other paper, published a year earlier, Battan studied the precipitation reaching the ground in his target from 1 p.m. to 6 p.m., particularly with reference to the indirectly measured height of the cloud base.

Panels I and II of Table 4 give data taken from Battan's Tables 7 and 8 referring to Programs 1 and 2, respectively. The three lines of each table refer to days with cloud bases "low," "medium," and "high" as indirectly measured by the so-called "dew-point spread."

The six categories of experimental days with low, medium and high cloud bases during the two Programs of the experiment are unambiguous in showing seed day deficiencies of rain in the target. Somewhat contrary to the conclusion of Battan, this fact could hardly be ascribed to chance. In the absence of effects of seeding and given strict randomization, the probability of the observed results is $(1/2)^6 = 0.016$, which is a respectable one tail significance probability.

Panel III of Table 4 represents a combination of Panels I and II. Here the estimated percent effect given in the last column is unambiguous: the higher the cloud base, the larger the loss of rain ascribable to seeding. This result suggests that during Battan's seeding in the early afternoons the appropriate level winds over the Santa Catalinas must have been weak. In consequence, the 5-hour precipitation amounts, 1 p.m. to 6 p.m., on which Battan's Tables 7 and 8 are based, reflect the full weight of the "precipitation break" phenomenon recorded by Simpson and Dennis.

This concludes the arguments supporting the hypothetical mechanism of far-away effects of local cloud seeding. This mechanism is based on the Simpson-Dennis phenomenon of "precipitation break." However, in addition to this phenomenon the two authors mention another interesting phenomenon labeled "orphan anvil."

> "In both tropics and temperate latitudes 'orphan anvils' from natural cumulo-nimbus clouds are found several hundred miles and many hours from their site of origin. Figure 29 shows an

TABLE 4

Dependence of the apparent effects of seeding at the Arizona experiment on the indirectly measured height of the cloud base, rain from 1 pm. to 6 pm.

PANEL I. Data for Program I

	Seeded days		Not seeded days		Percent effect
Cloud base	No.	Mean rain	No.	Mean rain	100 (S-NS)/NS
"low"	25	0.071	28	0.078	- 9
"medium"	20	0.036	18	0.062	-42
"high"	23	0.013	22	0.034	-62

PANEL II. Data for Program II

"low"	17	0.086	10	0.144	-40
"medium"	14	0.035	19	0.067	-48
"high"	6	0.028	8	0.041	-32

PANEL III. Height of cloud base and the apparent effect of seeding at the Arizona experiment. Data for both programs combined.

"low"	42	0.077	38	0.095	-19
"medium"	34	0.036	37	0.065	-45
"high"	29	0.016	30	0.036	-55

extensive anvil streaming out from an exploding seeded cumulus in Florida, a not uncommon event...In addition to their nucleating potential, 'orphan anvils' could have important radiative impacts. Where solar radiation striking the ground directly maintains convection, as over Florida in Summer, the shade of a single anvil often wipes out cumuli over a sizeable fraction of the southern peninsula extending outward in any direction from the target area, depending on winds aloft."

The photograph of an orphan anvil in Figure 29 of the two authors looks quite convincing and it is obvious that this phenomenon can be basic in a mechanism of the far-away effects of local cloud seeding. The problem is to secure data of a reasonably randomized experiment including high level winds, orphan anvils and rainfall in far-away localities.

<u>Mogrid Evidence of Unexpected Far-Away Effects of Local Seeding</u>

As already mentioned, the methodology used in documenting far-away effects of local seeding both at Grossversuch III and in the Arizona experiment is quite crude. The difference between wind directions on two days, say D_1 and D_2, may be minute and yet a far-away locality, such as Zürich or Walnut Gulch, may be considered "downwind" on day D_1 and "upwind" on D_2.

The mogrid methodology (10) permits one to study the "downwindedness" or "upwindedness," etc., of far-away effects defined with a much greater precision. However, this advantage must be paid for. The price is that the results do not apply to any specified locality at a known distance from the site of seeding. They apply to <u>categories</u> of localities which on particular days of an experiment are within a specified range of distances from the site of seeding and within a specified range of angles from the day's wind direction.

The three panels of Figure 7 exemplify the mogrid methodology in studying the far-away effects in Grossversuch III (two panels on top) and in the Arizona experiment (the lowest panel). There are 2 ranges of distances: from 0 to about 140 km. and from 140 km. to about 280 km. These are combined with 4 ranges of the angle of winds: -45° to +45° from the day's wind direction at a specified level ("downwind"), from 45° to 135° ("to the right," etc.). In consequence, each panel of Fig. 7 provides room for evaluation results in eight "cells". These cells are described as "far (or near) downwind," as "far (or near) to the right," etc.

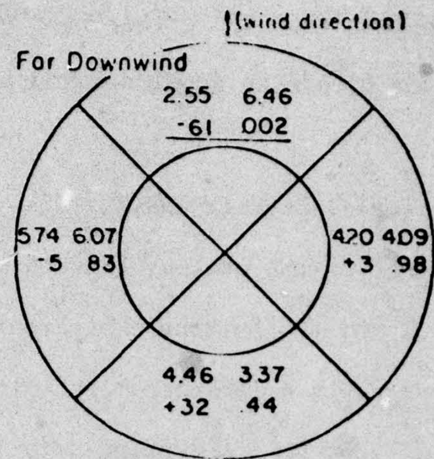
The mogrids for Grossversuch III are based solely on raingage data from the six shaded areas in Fig. 1 other than Milan. For this reason there are no evaluation results for the four "near" cells.

The four numerical entries in particular cells are written in two lines. Each top line gives mean rainfall on days with seeding and that on days without seeding. The lower line gives the estimated percent effect, which can be positive or negative. The second entry is the two-tail significance probability. Cases of significance are marked by underlining.

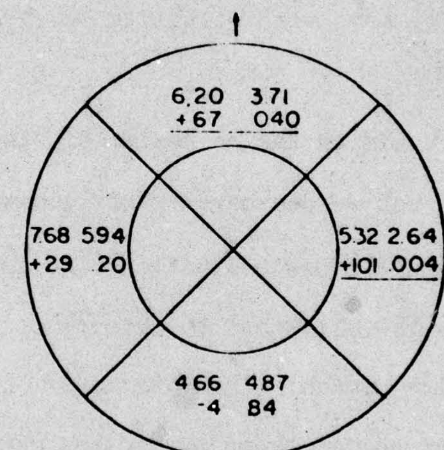
As an illustrative example, consider the top panel of Fig. 7. It corresponds to Grossversuch III days with uninhibited updrafts, for which Table 2 exhibits a substantial prevalence of negative apparent effects of seeding, both with southerly and with northerly winds, none of them significant. Contrary to this, the far-downwind cell shows a highly significant 61% deficiency of seed day rain ascribable to seeding. How come? There are two reasons for this contrast. One is that the evaluations in Table 2 are based on only 47 days with southerly winds and on 44 days with northerly winds, too few to achieve a substantial power of the tests used. The other reason for the inconclusiveness of Table 2 may well be the crudeness of determining the degree of "downwindedness": the

Fig. 7

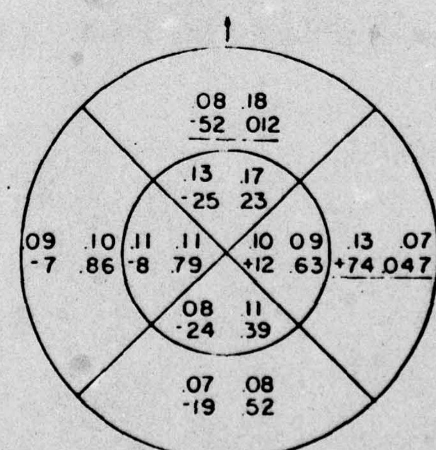
MOVING GRID RESULTS FOR
GROSSVERSUCH III
AND FOR ARIZONA EXPERIMENTS



GROSSVERSUCH III
UNINHIBITED UPDRAFTS



GROSSVERSUCH III
STABILITY LAYERS



ARIZONA EXPERIMENTS
FIRST DAYS

errors may have been in excess of 100°! Contrary to this, the mogrid methodology uses the total 47 + 44 = 91 days. Also, the error in determining "downwindedness," etc. had to be less than 45° either way. While not too impressive for surveyors, this degree of precision appears encouraging for large scale atmospheric motions.

The three panels of Figure 7 exhibit indications of two interesting atmospheric phenomena. One is the analogy between days with uninhibited updrafts at Grossversuch III and the Arizona experiment: in both cases the far downwind cell is marked by a large and significant apparent loss of rain ascribable to seeding. Another interesting detail is the presence of large and significant rainfall increases in the far cells to the right of the days' wind direction for days with stability layers in Grossversuch III and also for Arizona.

The question is what could be the mechanism of these differences in rainfall on seeded and not seeded days? This question is of particular interest for Arizona where all other evaluations indicated losses of rain ascribable to seeding. As is well known to meteorologists, there are two distinct classes of summer convective clouds: the "air mass" and the "frontal" clouds. Could it be that seeding of one of these categories decreases rain in the far downwind areas and that seeding of the other increases rain in the far areas to the right of the day's wind direction? And again: What is the mechanism of this phenomenon?

SUMMARY

As indicated in (1), the analysis of two seven-summer long experiments brought out indications of very strong effects of cloud seeding on rainfall. The two experiments, one in Switzerland and the other in Arizona, differed in many aspects. Yet, a collation of findings, dispersed in earlier publications, reveals certain patterns of apparent effects of seeding that are common to both experiments. It appears likely that these patterns reflect an unexpected real atmospheric phenomenon: "local" cloud seeding affects the rainfall in far-away localities to a greater extent than it does in the intended target.

While very relevant to the development of a reliable cloud seeding technology, the above findings are not mentioned in the vast literature on weather modification. In particular, this is the case of the recently published two-volume document (2), The Management of Weather Resources, prepared by the Weather Modification Advisory Board appointed by the U.S. Secretary of Commerce. I am appreciative of the Board's efforts, especially of its Vol. II, that summarizes the findings of its Statistical Task Force. In particular, I applaud the following three statements: (i) "...randomization has come to be recognized as an essential part of gathering trustworthy data about weather modification," (ii) "...randomization...needed if we are to be able to use the results as solid evidence," (iii) "The details (of experiments)--not just summaries--need to be available."

Statements (i) and (ii) are clear and unambiguous. However, I feel that statement (iii) requires illustrations. Roughly, there are two types of "details" frequently missing in the cloud seeding literature. One type involves the actual performance of an experi-

ment, the original data and the methodology used for the evaluation. Not infrequently, these details are hard to get. A somewhat different type of missing detail is illustrated by an article in the volume Legal and Scientific Uncertainties of Weather Modification (Ed. W.A. Thomas, Duke University Press, 1977). The article in question is authored by L.J. Battan. Its title is "The Scientific Uncertainties: A Scientist Responds." On p. 28, we read: "I hasten to point out that data from a number of carefully done commercial seedings strongly suggest that the person who paid for the operation got a fair return on the investment." This remark, representing the opinion of Professor Battan, is an interesting detail. However, I miss another detail. This is that Professor Battan performed a cloud seeding experiment lasting seven summers, that his own evaluation for the first four-summer long "Program" indicated 30% less rain on days with seeding than on those without, and that his own evaluation of the second "Program" of three summers also indicated a 30% deficiency of rain on days with seeding. My feeling is that this missing detail of Professor Battan's 5-page "...A Scientist Responds" is rather relevant for a conference "On Legal and Scientific Uncertainties..." Also, it seems important for the government and for the public at large.

Regretfully, a tendency to accept reports without insisting on "details" is reflected in Vol. I of the Advisory Board's Report to the U.S. Secretary of Commerce. While one year of intense study by the Board may seem long, it is not sufficient for gathering all the important details and for their appraisal. As stated in my article (1), the formulation of a realistic national policy on weather modification requires the "Establishment of at least two philosophically different interdisciplinary research groups, including statisticians versed in experimental work, perhaps members of the National Academy of Sciences, with a special mission to reevaluate the data of as many already performed cloud seeding experiments as possible, and continuation of properly planned experimentation. The suggested research groups should have unlimited access to the same data and have facilities for personal meetings to exchange ideas. They should be funded from sources other than those engaged in funding cloud seeding." To be effective, this multigroup project should last not just one but at least three years. Hopefully, such a multigroup project would examine the indications of the impressive far-away effects of local cloud seeding, including the studies made in the Berkeley Statistical Laboratory. Even with the greatest care blunders are difficult to avoid.

I am grateful to several scholars who commented on the preliminary draft of the present article. In particular, they pointed out the inadequacy of the original version of the Summary.

A letter of Professor Battan, dated October 30, 1978, generally disapproving the present article, contends that the quotation from his article ("I hasten to point...") is taken out of context. Professor Battan suggests that I include the rest of the relevant passage. It reads as follows.

> "In many other operations and experiments, it is impossible to tell. It really is somewhat like going to a physician when you are not feeling well. You receive an examination and a prescription and, if three days later you feel better, you figure you got your money's worth."

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